# Material Estimates for SVXII Hybrids and Portcards

Lilian Chen, Amy Connolly

*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*

We have calculated the amount of material in the SVXII hybrids, portcards, and cables, quantified as the radiation length averaged over the area of each part. We also include the radiation length of each unassembled part, along with the details of all surface mount components to allow one to simulate the material in these parts in a more detailed way. We include details of material estimates for thick film printed circuitry, surface mount components, solder, Elco connectors, cables and DOIMs.

## I. OVERVIEW

The hybrids and portcards are BeO substrates with thick film passive printed circuitry. The hybrids contain 2 printed silver layers, one silver-gold transition layer, 3 gold trace layers, and one layer with printed solder pads. Between these metal layers are layers of dielectric. There are 10 different hybrid types, one $\phi$-type and one $z$-type to be glued on the $\phi$ and $z$ sides of each of the five SVXII silicon layers (numbered Layers 0-4). For each SVXII layer (except Layer 3), the $\phi$ hybrids have the same printed circuitry as their $z$ partners (since they hold the same number of chips) the only difference being a longer substrate for the $\phi$ hybrids. The Layer 3 $\phi$ hybrids hold 6 chips, and their $z$ partners hold 4 chips, so the circuitry for these two hybrids differ.

Printed on the portcards are three silver layers, one silver-gold transition layer and 4 gold trace layers, with eight dielectric layers in between. This includes two dielectric layers between the analog and digital power planes and two dielectric layers after the gold-silver transition layer. The portcards are double-sided (circuitry printed on both the front and the back). Vias connect the two sides through holes in the substrate.

Hybrids and portcards both hold surface mount components (resistors and capacitors) soldered to pads on the surface. Silver epoxy secures the appropriate number of SVX3d chips and fingers to each hybrid type, and trancievers, DDR chips, and transistors to the portcards. HDI flex cables are soldered to the phi hybrids and attached to the portcards with Elco connectors.

Here the amount of material in each hybrid type, portcard and cable is estimated, averaged over the area of the substrate. In other words, the total radiation length of a hybrid or portcard is calculated as though all of the material on the part is smeared over the entire surface of the substrate. Included in the calculation were contributions from the substrate, metal and dielectric layers, solder, epoxy, chips, fingers, resistors, capacitors, and Elco connectors. The presence of these higher density components has a large impact on the tails of the distribution of radiation lengths traversed by a particle [4]. Therefore, in addition to including an estimate of the radiation length of a hybrid or portcard after smearing, we also include the radiation length of each unassembled part alone (with all metal inks and dielectrics smeared over the surface) so that one may simulate the parts with a more complete picture using the details of the components described here.

Radiation lengths for elements were estimated using the following equation [1]:

$$X_0 = \frac{716.4 g/cm^2 A}{Z(Z+1)\ln 287/\sqrt{Z}} \tag{1}$$

and for compounds or mixtures,

$$1/X_0 = \sum w_j/X_j \tag{2}$$

where $X_j$ and $w_j$ are the radiation length and fraction by mass of the $j$th element. Equation 2 was also used for calculating the total effective radiation length for an entire part, where the sum is over all chips, components, metal and dielectric layers, etc. Densities were taken from the CRC handbook [2] unless otherwise stated. We aimed for a 10% resolution on the total amount of material in each hybrid or portcard.

## II. HYBRIDS AND PORTCARDS

Table I lists the principal materials contained in the hybrids, portcards and cables, their densities and radiation lengths.

### A. Substrate

For both hybrids and portcards, the nominal thickness of the substrate is $500\mu$. After measuring several portcard and hybrid substrates, we find that the substrate thicknesses are closer to $520\mu$. The substrates for the $\phi$ hybrids are of course longer then their $z$ partners, with essentially no additional components. Therefore, for the calculational method used in this note, the radiation length (on average) seen by a particle as it traverses a $\phi$ hybrid is smaller than the radiation length seen by a particle traversing a $z$ hybrid. Note that when a ladder is constructed an additional 'z-piece' of BeO is added to the z side. This extra z-piece is not accounted for in this note. In addition, there is a new port card cover made of carbon fiber which will be added to the portcard. This is not yet included in our calculations.

### B. Metal Ink

The first two metal layers in the SVXII hybrids are the shield layer (FC1, for Front Conductor 1) and power and ground planes (FC2). The third metal layer is a silver and gold transition layer (FC3a and FC3b), and the final three printed layers (FC4, FC5 and FC6) are gold traces. Silver was used instead of gold for the power and ground planes in order to minimize the amount of material in the hybrids. The thickness of each metal ink layer was measured at fabrication after firing, and was consistently $9-10\mu$. The fractional coverage of each ink layer was estimated from the design drawings. The effective thickness of a layer of ink was defined to be the thickness of the ink if it were smeared over the entire substrate. For example, if a gold ink layer which is $10\mu$ thick covers 30% of the substrate, then the effective thickness is $3\mu$. For these calculations, the gold ink was approximated to be pure gold and the silver ink, pure silver. The solder pads are PdAg. Vias connect neighboring metal layers through holes in the printed or laminated dielectric. These were considered in the calculations as well, each via being a cylinder the size of the hole in the dielectric which they fill.

The portcards contain three silver power and ground layers, one silver-gold transition layer, four gold trace layers, and one layer with PdAg solder pads, with the same properties as those for the hybrids described above.

### C. Dielectrics

Two different technologies were used for implementing dielectric layers on the hybrids. The first two front dielectric layers (FD1 and FD2) were printed, and all other dielectric layers (BD1 – printed on the back, FD3a, FD3b, FD4, and FD5) were laminated. These processes give different layer thicknesses after firing.

ESL 41010-25C was used for 3 out of 4 lamination layers on the hybrids and 3 out of 7 lamination layers on the portcards. All remaining lamination layers were printed with ESL 41020-25C. These inks have properties similar to glass, with a heavy metal component. ESL claims that 41010-25C contains <10% Pb (we use 10% in our calculations) and 41010-25 contains 10-20% BaO (we use 15%). The material data sheets indicate that the theoretical fired density of 41010-25 and 41020-25 are 3.06 g/cm$^3$ and 3.12 g/cm$^3$, respectively. From the densities of Pb and BaO, we conclude that the density of the remaining material in these inks is 2.9 g/cm$^3$. We take the radiation length of this remaining material to be the same as glass, 27.9 g/cm$^2$. We approximate that the laminated dielectrics have identical properties as the 41010-25 ink.

All dielectric layers on the portcard were laminated. The hybrids have a blank layer of dielectric laminated on the backside (BD1) to prevent excessive bowing of the substrate. This extra dielectric layer was not needed for the portcards since circuitry is already printed on both sides of the part.

During fabrication, hybrids for SVXII Layers 1 and 2 required a modification when

FD2 was accidentally printed over the entire hybrid surface, covering the analog ground plane for the chips. One additional silver layer was printed in order to reestablish this ground plane. These additional dielectric and silver layers were included in the mass estimates for Layer 1 and 2 hybrids.

Table II lists the dielectric thicknesses used for these calculations. The following cross-checks were done on hybrids to make sure that these thicknesses are not unreasonable. See Figure 1.

1. The depth of Section I + Section II was measured with a micrometer. These sections only include the substrate, and BD1. We find the thickness is 580 $\mu$. From the above table, we calculate that this thickness should be: $520\mu + 63.5\mu = 583.5\mu$.

2. The depth of Section VI was measured with a $10\mu$ resolution probe. This section is only FD4. We measure $70\mu$. This is consistent with the $63.5\mu$ laminated dielectric thickness in Table II.

3. We use the same $10\mu$ resolution probe to measure the height of Section IV. This Section contains FD2, FC3a, FC3b, FD3a, FD3b and FC4. The measured thickness is $210\mu$. We calculate:

$$40\mu + 10\mu + 63.5\mu + 63.5\mu + 10\mu = 187\mu.$$

4. The height of Section IV + Section V was measured, again to $10\mu$ precision. These sections contain all layers listed in 3, and FD4, FC5 and FD5. Measured thickness was $340\mu$.

$$187\mu + 63.5\mu + 10\mu + 63.5\mu = 324\mu.$$

5. We measured the thickness of the hybrid in the region where the chips are attached (Section I + Section II + Section III). This thickness is between $650\mu$ and $670\mu$. This region contains BD1, substrate, FC1, FD1 and FC2. We calculate:

$$63.5\mu + 520\mu + 10\mu + 40\mu + 10\mu = 643.5\mu.$$

6. The solder mask was measured with $\pm 2\mu$ precision to be $3\mu$.

So, after several checks against hybrid measured thicknesses, we conclude that the thicknesses in Table II are within 10% tolerance.

## III. COMPONENTS

Hybrids and portcards are assembled with surface mount components. A typical effective radiation length for components alone, smeared over a hybrid or portcard surface, is 14.5 $g/cm^2$.

### A. Solder

From the dimensions of the solder pads we calculate the area which solder is likely to occupy on each solder pad, and take the thickness of the solder to be $140\mu$. In order to arrive at this thickness, we weighed a portcard before and after adding the appropriate amount of solder to the the solder pads, and from the measured mass of the solder, deduced the thickness after estimating the area that the solder covers on the portcard.

Where Elco connectors are connected to the portcards, we assume the same solder volume as was measured from the cables (described below).

### B. Silver Epoxy

Chips and fingers were both attached to the hybrids with silver epoxy. We consider this silver epoxy to be pure silver, even though its non-metallic component is probably significant. This conservative assumption is justified because (even with this assumption) silver epoxy contributes less than 2% of the total calculated radiation length of a hybrid or portcard. We estimate that the silver epoxy covers as much area as the chips with a thickness of $50\mu$.

### C. Chips

Chips were approximated as blocks of pure silicon, with dimensions $12.1mm \times 6.4mm \times 350\mu$.

### D. Fingers

The fingers are made of an alumina ($AlO_2$) substrate with printed layers of dielectric and gold. Due to the small size of the fingers, we neglect the ink layers and assume the fingers are only blocks of $AlO_2$ with dimensions $1.2cm \times 0.1cm \times 375\mu$. This is justified because fingers contribute less than 2% of the total hybrid radiation length.

### E. Resistors

Rhom surface mount 0402 resistors were assembled on the hybrids. On the portcards, 0603 resistors were used as well. The data sheets for the surface mount resistors can be found at

http://www.rohm.com/products/databook/r/pdf/index.html.

The 0402 resistors assembled on the hybrids are manufacturer number MCR01. The dimensions of these resistors which we have measured with a micrometer are: $1000\mu \times 520\mu \times 325\mu$, consistent with the dimensions given on the data sheet. We measure the mass of an 0402 resistor to be $6.4 \times 10^{-4}g$.

Figure 2 is the page from the manufacturer's data sheets which shows a cross-section of an 0402 resistor. The resistor is made of an alumina ($Al_2O_3$) substrate (probably 250 $\mu$) with a thick dielectric glaze of ruthenium. The edges of the resistor (to $250\mu$ from the edge) have a thick film layer of PdAg to make a primary electrode, covered with a Ni coated secondary electrode, covered with an external electrode made of Sn and Pb. The thicknesses of these material layers were adjusted (started from educated estimates from past experience with thick film technology [3]) to approximately match the measured thickness and mass of the resistors. Table III lists the dimensions and densities of the materials which make up the resistors. For the metals which wrap around the side of the resistor, the "length" is the length which the strip of metal would have if it were unfolded from the substrate. Note that the total thickness of the resistor itself is the substrate thickness, added to twice the thicknesses of the PdAg, Ni and PbSn layers. The total density of the resistor is the sum of the densities of the materials which make it up, weighted by volume. The total radiation length is calculated from Equation 2. Total calculated mass, after adjusting the thicknesses, for an 0402 resistor is $6.7 \times 10^{-4} g$ which is well within 10% of the measured mass. We use the same effective density and radiation length for 0603 resistors as well.

### F. Ceramic Capacitors

Rhom ceramic capacitors were assembled on both hybrids and portcards. Those assembled on portcards include 0402, 0805, and 0603 parts and hybrids, 1206, 0805, and 0603. The data sheet for the surface mount capacitors can be found at

http://www.rohm.com/products/databook/c/pdf/index.html.

From the data sheets, we could only conclude that the bulk of the capacitor was made of either Titania ($TiO_2$) or Barium Titanate ($BaTiO_3$), so we calculated the mass of the capacitors given each hypothesis and compared with the measured mass to deduce which material was most likely in the capacitors.

Table IV summarizes the dimensions and densities used for each material in the 0805 capacitors, including both bulk material hypothesis, $BaTiO_3$ and $TiO_2$.

The calculated mass with the $BaTiO_3$ hypothesis was 0.017 g and with the $TiO_2$ hypothesis it was 0.011 g. The measured mass of the 0805 capacitor was 0.017 g, so we conclude that the capacitor was made of $BaTiO_3$.

The radiation length of $BaTiO_3$ is 11.3 $g/cm^2$. Radiation lengths for all other materials have already been listed in earlier tables.

Since the capacitor was completely made of $BaTiO_3$, the total radiation length for all ceramic capacitors was taken to be just that of $BaTiO_3$: $11.3 g/cm^2$.

### G. Tantalum Capacitors

There are no tantalum capacitors on SVXII hybrids or portcards, but the calculation is shown here anyway since they are assembled on ISL hybrids. The data sheets for these capacitors may be found at

http://www.avxcorp.com/prodinfo_catlist.asp?l= 4&s1=1&s2=48&s3=125

and there is a nice summary of tantalum capacitor technology at

http://www.avxcorp.com/techinfo_documentdetail.asp?ID=25&Heading=BASIC+ TANTALUM+CAPACITOR+TECHNOLOGY&Category=TANTALUM

From the summary paper of tantalum technology, we conclude that the capacitors are primarily made of $MnO_2$ and $Ti_2O_5$. We weighed a number of 0805 capacitors and found an average mass of $2.78 \times 10^{-2} g$. The dimensions of the capacitor are roughly $2.0mm \times 1.35mm \times 1.35mm$ which gives a density of $2.78 \times 10^{-2} g/3.65mm^3 = 7.6 g/cm^3$. The density of $Ta_2O_5$ is $8.2 g/cm^3$ and the density of $MnO_2$ is $5.0 g/cm^3$, so we can conclude that the capacitor is roughly 80% $Ta_2O_5$ and 20% $MnO_2$, by volume. For $Ta_2O_5$, $X_0 = 8.0 g/cm^2$ and for $MnO_2$, $X_0 = 18.9 g/cm^2$, so we conclude that the effective radiation length for a tantalum capacitor is $8.6 g/cm^2$.

### H. Elco connectors

Elco brand connectors were used to connect the hybrids with the portcards. Two Elco plugs were attached to the end of each hybrid cable, each to be plugged into receptacles on the portcard. Since the portcard connects to hybrids from five SVXII layers, 10 Elcos are surface mounted on the portcard. At the cable end, the part number used is 24 5087 0309 00 861, and at the portcard end the part number is 14 5087 0309 40 861. There are 30 contacts on each connector.

The casing and leads for the Elco connectors are made of Polyphenelyne sulfide ($C_6H_6S$) and Phosphor Bronze (PCuSn), respectively. There were 30 leads each with approximate dimensions $0.2mm \times 5mm \times 0.2mm$ for a total volume of $6mm^3$. The density of PCuSn is $8.86g/cm^3$, so the total mass of the 30 leads is 0.053g. The total mass of a receptacle is 0.152 g, so the volume of the casing was taken to be whatever it had to be to make up the rest of the mass. This was $96mm^3$, consistent with the drawing on the data sheet. The radiation length of PCuSn is $8.86g/cm^2$ and that of $C_6H_6S$ is $24.2g/cm^2$ so the total effective radiation length of an elco connector receptacle is $18.25g/cm^2$. The average radiation length for an Elco plug is assumed to be the same.

### I. DOIMs

We approximate that the DOIMs are made of an $Al_2O_3$ substrate with plastic housing [5]. Details are summarized in Table V. There are 5 DOIMs assembled on each portcard.

### J. Hybrid and Portcard Results

Table VI shows for the portcards and for each hybrid type the effective thickness for each material (the thickness that component would have if it were smeared over the entire substrate), and the ratio $w_j/X_0$. This is the ratio of the fraction by mass to radiation length for that particular material. From Equation 2, the material with the largest value for this ratio will affect the total effective radiation length the most. By listing this ratio for each material, one can easily see which material contributes the most for a particular part. As mentioned above, effective radiation lengths are shown separately for unassembled and assembled parts.

Table VII summarizes total effective radiation lengths and other properties calculated for assembled hybrids and portcards. Calculations for unassembled parts are summarized in Table VIII. In order to judge how close these calculations are, total calculated masses are compared to measured masses, before and after assembly of any components. The mass estimates before and after assembly are consistent with measured values, within the desired 10% tolerance. There are also uncertainties in the measured masses of the parts due to low statistics (typically only 2 parts of each type were weighed) and due to wires, solder, etc. added to the parts for fixes as needed. The uncertainty associated with the measured mass of a hybrid or portcard is approximately 0.1 g.

## IV. HDI CABLES

Figure 3 is a cartoon of a typical HDI cable which brings power and signals between the hybrid and portcard. The radiation length of the HDI cables was estimated for each layer separately. The only important difference between cables is the dimensions, and relative ratios of materials. Table IX lists the effective thickness of each material in each cable type and the ratio $w_j/X_0$.

### A. Copper

The cables contain two layers of copper traces. The total area of copper traces was estimated from the design drawings for each cable design. The copper laminate is nominally $1/2oz./ft^2$ [3], so from the density of copper, we expect the thickness of the copper to be $17\mu$.

### B. Kapton

Aside from copper, the bulk of the cable is made up of kapton and glue. Kapton and glue were assumed to have the same density and radiation length. Material properties for Kapton were taken from [1]. The thickness of the cable in a region lacking shielding was measured with a micrometer. The difference between this measured thickness and twice the effective thickness of the copper layers is the thickness of the Kapton and glue.

The kapton has a larger thickness at the portcard end of the cable, for extra mechanical reinforcement. This extra volume of kapton was estimated and added to the total.

### C. External Wires

Wires are added externally to the cables to assure good power and ground connections from the one end of the cable to another. Wire diameters were $175\mu$ for hybrid layers 0 and 1, and $220\mu$ for layers 2,3 and 4. An appropriate wire length for each cable is used. We approximate that the wires are made entirely of copper.

### D. Shielding

Aluminum shielding was added along the length of the cables. This shielding is covered with kapton and glue. The total thickness of the aluminum + kapton and glue was measured from the thickness of the cable where the shielding is, minus the thickness of the cable where the shielding is not. The shield metal is nominally 13 $\mu$, so the kapton + glue is the difference.

### E. Solder

To estimate how much solder was added to the Elco connector fields, assembled cables were weighed, with and without Elco connectors soldered to them, and the mass of solder was taken to be the difference, minus the mass of an Elco connector. The mass of the solder on the cable was measured from this method is .015 g and the volume was adjusted to get this mass, assuming solder was is made of 33% Pb and 67% Tn by volume. The solder used to attach HDI cables to the hybrids was included in the hybrid calculations, and not in the calculations for the cables.

### F. Ground Straps

The ground straps are made through the same production processes as the cables. They are L-shaped "cables", with a single thick copper trace along their length.

### G. Portcard Pigtail Cables

Cables similar in material makeup to the HDI cables are soldered to the portcards. These are the interface to the cabling which goes to the junction cards. No external wires are attached to these cables, and no connectors are used at the portcard end. Therefore, here we approximate that these cables are made of kapton and copper alone. By measuring the thickness of the cable in a region with no copper, we find that the kapton thickness is 279 $\mu$. In a region of the cable which contains both kapton and copper, we measure the thickness to be 457 $\mu$. Therefore the copper thickness is 178 $\mu$.

Three connectors are attached to this cable on the end which connects to the junction card cables. These connectors are not included in our calculations at this time. Nor is the G10 which provides strain releif behind the connectors

### H. Cable Results

The calculated effective radiation lengths for the cables are summarized in Table X. Calculated masses are compared to measured masses for before and after assembly of wires and elco connectors.

## V. CONCLUSIONS

We supply an estimate for the material contained in SVXII hybrids and portcards. The results are quantified as a total radiation length for each part, before and after assembly of components. After comparing our mass calculations to measured, we conclude that our estimates are within the 10% resolution we had hoped to maintain.

## VI. ACKNOWLEDGEMENTS

We wish to acknowledge Maurice Garcia-Sciveres for much advice throughout this study. We are also grateful to Stephan Van den Brink for his careful review of our calculations.

[1] Particle Data Group, “Review of Particle Properties,” Phys. Rev. D50(1994) 1254.

[2] Chemical Rubber Company, “CRC handbook of chemistry and physics,” CRC Press, 1998.

[3] Personal communication, Maurice Garcia-Sciveres.

[4] David Stuart, CDF/DOC/TRACKING/PUBLIC/5268

[5] These DOIM material estimates were performed by Stephan Van den Brink.

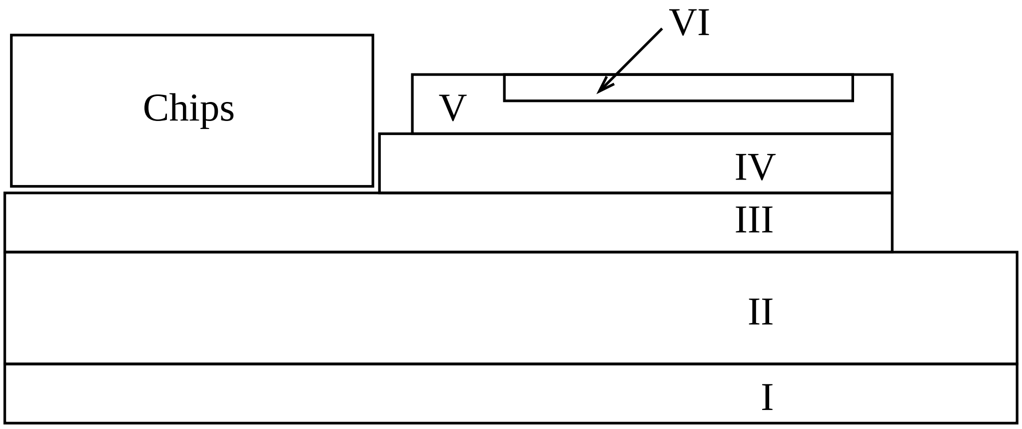
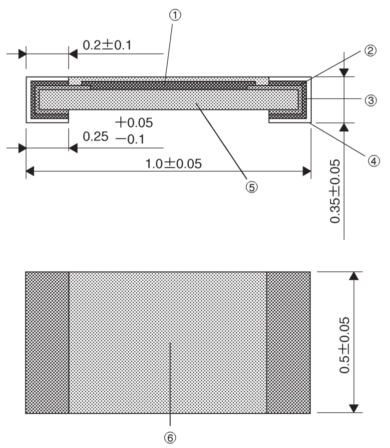



FIG. 1. Side view of a $\phi$ hybrid. Section I is the dielectric printed on the back side of the hybrid and Section II is the substrate. Section III contains FC1, FD2, and FC2. Section IV contains FD2, FC3a, FC3b, FD3a, FD3b, and FC4. Section V contains FD4, FC5, FD5, FC6 and the solder mask layer. Section VI represents the ledge which is cut out of the side of the hybrid to expose FC4 traces which are wire bonded to the jumper. For a $z$ hybrid, Sections I and II do not protrude beyond Sections III, IV and V.

Resistors **MCR01**

●External dimensions (Units: mm)




| No. | Material |
|---|---|
| ① | Thick dielectric glaze of ruthenium (only silver used for jumper) |
| ② | Thick film of palladium-silver for primary electrode |
| ③ | Nickel-coated secondary electrode |
| ④ | External electrode coated with tin and lead |
| ⑤ | Alumina substrate |
| ⑥ | Overcoating |

FIG. 2. Cross-section of Rhom 0402 surface mount resistor taken from the manufacturer's data sheets.

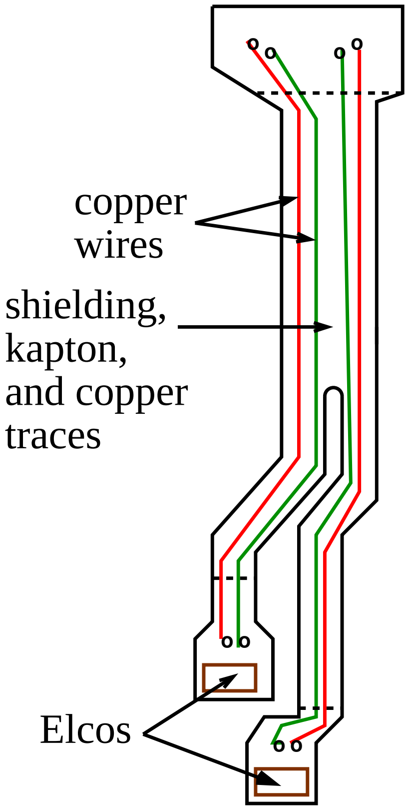



FIG. 3. A "typical" HDI cable. Cables for SVXII Layer 0 and Layer 1 have two pairs of wires along their length as shown, and cables for Layers 2-4 have only one pair. The Elco connectors attach the cables to the portcards. The cables are soldered to the hybrids at the opposite end. The dashed lines show where the aluminum sheilding typically ends.

| Material | $\rho (g/cm^3)$ | $X_0 (g/cm^2)$ |
|---|---:|---:|
| BeO | 2.85 | 41.1 |
| Au | 19.3 | 6.5 |
| Ag | 10.5 | 9.0 |
| PdAg | 11.3 | 9.3 |
| Dielectric 41010-25C | 3.06 | 20.8 |
| Dielectric 41020-25C | 3.12 | 21.1 |
| Kapton | 1.42 | 40.6 |
| Cu | 8.9 | 12.9 |
| Al | 2.7 | 24.0 |
| Pb | 11.3 | 6.3 |
| Sn | 7.3 | 9.0 |
| Si | 2.3 | 21.8 |

TABLE I. Summary of materials in the hybrids, portcards and cables.

| | |
|---|---:|
| dielectric tape | 63.5 $\mu$ |
| printed dielectric | 40$\mu$ |
| printed metal | 10$\mu$ |
| solder mask | 4$\mu$ |

TABLE II. Actual thicknesses of metal inks and dielectrics in the hybrids and portcards.

| Material | Length (mm) | Width (mm) | Thickness (mm) | $\rho(g/cm^3)$ | $X_0(g/cm^2)$ |
|---|---|---|---|---|---|
| Ru | 0.9 | 0.52 | 0.009 | 12.3 | 9.7 |
| PdAg | 0.76 | 0.52 | 0.009 | 11.26 | 9.3 |
| Ni | 0.79 | 0.52 | 0.001 | 8.9 | 13.0 |
| PbSn | 1.55 | 0.52 | 0.294 | 8.5 | 7.1 |
| $SiO_2$ | 0.7 | 0.52 | .005 | 2.32 | 27.3 |
| Total | | | 0.322 | 4.40 | 20.5 |

TABLE III. Dimensions, densities and radiation lengths used for the surface mount resistors.

| Material | Length (mm) | Width (mm) | Thickness (mm) | $\rho(g/cm^3)$ | $X_0(g/cm^2)$ |
|---|---|---|---|---|---|
| Ni | 1.8 | 1.22 | 0.002 | 8.9 | 13.0 |
| PbSn | 1.7 | 1.22 | 0.002 | 8.5 | 7.1 |
| Ag | 1.6 | 1.22 | 1.15 | 10.5 | 9.2 |
| $BaTiO_3$ | 2.1 | 1.22 | 1.15 | 5.8 | 11.3 |
| $TiO_2$ | 2.1 | 1.22 | 1.15 | 3.8 | |
| Total ($BaTiO_3$) | | | | 5.8 | 11.3 |
| Total ($TiO_2$) | | | | 3.9 | |

TABLE IV. Dimensions, Densities and Radiation Lengths used for surface mount capacitors, with two different material hypothesis listed.

| Material | Volume ($cm^3$) | $\rho (g/cm^3)$ | $X_0 (g/cm^2)$ |
|---|---:|---:|---:|
| $Al_2O_3$ | 0.08 | 3.9 | 27.9 |
| PBT Plastic | 0.27 | 1.3 | 40.0 |
| Total | | | 33.1 |

TABLE V. Dimensions, Densities and Radiation Lengths used for DOIMs.

| 2p Hybrid | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 3.7 | .0038 |
| Silver | 17.6 | 0.0071 |
| Dielectric 41010-25C | 83.9 | 0.0044 |
| Dielectric 41020-25C | 141.0 | 0.0072 |
| Components | 103.7 | 0.0105 |
| BeO | 520 | 0.0125 |
| PdAg | 0.8 | 0.0004 |
| Total | 887 | 1/21.8 |
| Total Unassembled | 766 | 1/23.9 |
| | | Area = 7.43 $cm^2$ |

| 2z Hybrid | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 4.9 | 0.0045 |
| Silver | 23.3 | 0.0084 |
| Dielectric 41010-25C | 111.5 | 0.0051 |
| Dielectric 41020-25C | 166.5 | 0.0075 |
| Components | 159.0 | 0.012 |
| BeO | 520 | 0.011 |
| PdAg | 1.1 | 0.0004 |
| Total | 986 | 1/20.4 |
| Total Unassembled | 826 | 1/22.2 |
| | | Area = 5.59 $cm^2$ |

| 3p | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 3.3 | 0.0034 |
| Silver | 20.7 | 0.0083 |
| Dielectric 41010-25C | 83.3 | 0.0043 |
| Dielectric 41020-25C | 152.9 | 0.0077 |
| Components | 115 | 0.0096 |
| BeO | 520 | 0.012 |
| PdAg | 0.7 | 0.0003 |
| Total | 896 | 1/21.7 |
| Total Unassembled | 780 | 1/23.5 |
| | | Area = 11.29 $cm^2$ |

| 3z | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 4.4 | 0.0040 |
| Silver | 27.6 | 0.0097 |
| Dielectric 41010-25C | 111.5 | 0.0050 |
| Dielectric 41020-25C | 183.0 | 0.0081 |
| Components | 153.5 | 0.011 |
| BeO | 520 | 0.011 |
| PdAg | 0.9 | 0.0003 |
| Total | 1000 | 1/20.3 |
| Total Unassembled | 847 | 1/21.9 |
| | | Area = 8.44 $cm^2$ |

| 5p | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 3.7 | 0.0037 |
| Silver | 20.8 | 0.0083 |
| Dielectric 41010-25C | 83.9 | 0.0043 |
| Dielectric 41020-25C | 153.6 | 0.0077 |
| Components | 118.3 | 0.0095 |
| BeO | 520 | 0.012 |
| PdAg | 0.8 | 0.0003 |
| Total | 901 | 1/21.6 |
| Total Unassembled | 782 | 1/23.3 |
| | | Area = 17.8 $cm^2$ |

| 5z | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 4.9 | 0.0043 |
| Silver | 27.6 | 0.0096 |
| Dielectric 41010-25C | 111.5 | 0.0050 |
| Dielectric 41020-25C | 183.1 | 0.0081 |
| Components | 157 | 0.011 |
| BeO | 520 | 0.011 |
| PdAg | 1.0 | 0.0004 |
| Total | 1005 | 1/20.3 |
| Total Unassembled | 847 | 1/21.8 |
| | | Area = 13.4 $cm^2$ |

| 6p | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 3.6 | 0.0037 |
| Silver | 17.4 | 0.0071 |
| Dielectric 41010-25C | 84.8 | 0.0044 |
| Dielectric 41020-25C | 142.0 | 0.0072 |
| Components | 123 | 0.0103 |
| BeO | 520 | 0.013 |
| PdAg | 0.7 | 0.0003 |
| Total | 891 | 1/22.0 |
| Total Unassembled | 768 | 1/24.0 |
| | | Area = 21.1 $cm^2$ |

| 4z | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 3.8 | 0.0039 |
| Silver | 15.7 | 0.0063 |
| Dielectric 41010-25C | 100.2 | 0.0051 |
| Dielectric 41020-25C | 166.0 | 0.0083 |
| Components | 106 | 0.0086 |
| BeO | 520 | 0.012 |
| PdAg | 0.8 | 0.0003 |
| Total | 913 | 1/22.3 |
| Total Unassembled | 806 | 1/24.0 |
| | | Area = 16.1 $cm^2$ |

| 7p | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 3.5 | 0.0037 |
| Silver | 17.4 | 0.0072 |
| Dielectric 41010-25C | 83.3 | 0.0044 |
| Dielectric 41020-25C | 140.4 | 0.0073 |
| Components | 110 | 0.0092 |
| BeO | 520 | 0.013 |
| PdAg | 0.7 | 0.0003 |
| Total | 875 | 1/22.3 |
| Total Unassembled | 765 | 1/24.0 |
| | | Area = 26.8 $cm^2$ |

| 7z | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 4.5 | 0.0043 |
| Silver | 22.6 | 0.0084 |
| Dielectric 41010-25C | 108 | 0.0051 |
| Dielectric 41020-25C | 163 | 0.0076 |
| Components | 143 | 0.011 |
| BeO | 520 | 0.011 |
| PdAg | 0.97 | 0.0004 |
| Total | 962 | 1/20.9 |
| Total Unassembled | 818 | 1/22.6 |
| | | Area = 20.7 $cm^2$ |

| | | |
|---|---|---|
| Portcards | | |
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Gold | 15.1 | 0.0049 |
| Silver | 3.9 | 0.0033 |
| Dielectric 41010-25C | 187.9 | 0.0078 |
| Dielectric 41020-25C | 142.0 | 0.0054 |
| Components | 2.0 | 0.0041 |
| BeO | 520 | 0.010 |
| PdAg | 0.9 | 0.0003 |
| Elcos | 13.5 | 0.0032 |
| DOIMs | 49 | 0.0040 |
| Total | 935 | 1/23.2 |
| Total Unassembled | 870 | 1/31.6 |
| | | Area = 71.0 $cm^2$ |

TABLE VI. Summary of material calculations for the hybrids and portcards.

| Hybrid Type | Eff. $X_0$ ($g/cm^2$) | Density ($g/cm^3$) | Eff. $X_0$ (cm) | Fract. $X_0$ (%) | Assembled Calc Mass (g) | Assembled Meas Mass (g) |
|---|---|---|---|---|---|---|
| 2p | 21.9 | 3.25 | 6.7 | 1.32 | 3.47 | 3.60 |
| 2z | 20.4 | 3.32 | 6.2 | 1.60 | 1.83 | 2.15 |
| 3p | 21.8 | 3.25 | 6.7 | 1.33 | 4.48 | 4.50 |
| 3z | 20.4 | 3.33 | 6.1 | 1.63 | 2.81 | |
| 5p | 21.7 | 3.23 | 6.7 | 1.35 | 6.49 | 6.75 |
| 5z | 20.3 | 3.30 | 6.1 | 1.64 | 4.45 | 4.45 |
| 6p | 22.1 | 3.23 | 6.8 | 1.31 | 7.63 | 7.60 |
| 4z | 22.4 | 3.21 | 7.0 | 1.31 | 4.71 | 4.55 |
| 7p | 22.3 | 3.22 | 6.9 | 1.26 | 8.93 | 9.00 |
| 7z | 21.0 | 3.28 | 6.4 | 1.50 | 6.52 | |
| Portcard | 23.2 | 2.81 | 8.2 | 1.13 | | |

TABLE VII. Assembled hybrid and portcard properties

| Hybrid Type | Eff. $X_0$ $(g/cm^2)$ | Density $(g/cm^3)$ | Eff. $X_0$ (cm) | Fract. $X_0$ (%) | Unassmbld Calc Mass (g) | Unassmbld Meas Mass (g) |
|---|---|---|---|---|---|---|
| 2p | 23.9 | 3.18 | 7.5 | 1.02 | 1.81 | 1.76 |
| 2z | 22.2 | 3.25 | 6.8 | 1.21 | 1.51 | 1.50 |
| 3p | 23.5 | 3.20 | 7.4 | 1.06 | 2.82 | 2.72 |
| 3z | 21.9 | 3.27 | 6.7 | 1.26 | 2.34 | 2.33 |
| 5p | 23.3 | 3.21 | 7.3 | 1.07 | 4.47 | |
| 5z | 21.8 | 3.28 | 6.6 | 1.27 | 3.73 | |
| 6p | 24.0 | 3.17 | 7.6 | 1.02 | 5.16 | 5.06 |
| 4z | 24.0 | 3.16 | 7.6 | 1.06 | 4.11 | 4.00 |
| 7p | 24.0 | 3.17 | 7.6 | 1.01 | 6.52 | 6.42 |
| 7z | 22.6 | 3.23 | 7.0 | 1.17 | 5.49 | 5.40 |
| Portcard | 25.7 | 3.16 | 8.1 | 1.1 | | |

TABLE VIII. Unassembled hybrid and portcard properties

| | | |
|---|---|---|
| Layer0 | | |
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Kapton | 241 | 0.011 |
| Cu | 15.7 | 0.019 |
| Al | 9.8 | 0.001 |
| Solder | 1.1 | 0.0015 |
| Elcos | 58.6 | 0.013 |
| Total | 326 | 1/21.2 |
| | | Area = 16.4 $cm^2$ |

| | | |
|---|---|---|
| Layer1 | | |
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Kapton | 242 | 0.011 |
| Cu | 16.9 | 0.020 |
| Al | 9.5 | 0.001 |
| Solder | 1.2 | 0.002 |
| Elcos | 68.5 | 0.015 |
| Total | 338 | 1/20.7 |
| | | Area = 14.0 $cm^2$ |

| Layer2 | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0 (cm^2/g)$ |
| Kapton | 237 | 0.012 |
| Cu | 16.0 | 0.019 |
| Al | 9.1 | 0.0014 |
| Solder | 1.0 | 0.0015 |
| Elcos | 54.1 | 0.013 |
| Total | 317 | 1/21.4 |
| | | Area = 17.7 $cm^2$ |

| Layer3 | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0 (cm^2/g)$ |
| Kapton | 243 | 0.013 |
| Cu | 12.6 | 0.016 |
| Al | 9.5 | 0.002 |
| Solder | 1.0 | 0.002 |
| Elcos | 48.7 | 0.013 |
| Total | 315 | 1/22.6 |
| | | Area = 19.7 $cm^2$ |

| Layer4 | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Kapton | 228 | 0.011 |
| Cu | 16.5 | 0.019 |
| Al | 7.8 | 0.001 |
| Solder | 1.0 | 0.002 |
| Elcos | 54.7 | 0.013 |
| Total | 307 | 1/21.3 |
| | | Area = 17.6 $cm^2$ |

| Ground Strap | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Kapton | 113 | 0.013 |
| Cu | 17 | 0.040 |
| Total | 130 | 1/19.8 |
| | | Area = $2.35cm^2$ |

| Portcard Cables | | |
|---|---|---|
| Material | Effective Thickness ($\mu$) | $w_j/X_0(cm^2/g)$ |
| Kapton | 279 | 0.004 |
| Cu | 178 | 0.062 |
| Total | 457 | 1/14.9 |
| | | Area = $23.0cm^2$ |

TABLE IX. Summary of material calculations for the cables.

| Cable | Eff. $X_0$ $(g/cm^2)$ | Density $(g/cm^3)$ | Eff. $X_0$ (cm) | Fract. $X_0$ (%) | Unassmbld Calc Mass (g) | Unassmbld Meas Mass (g) | Assembled Calc Mass (g) | Assembled Meas Mass (g) |
|---|---|---|---|---|---|---|---|---|
| Layer 0 | 20.8 | 1.96 | 10.7 | 0.31 | 0.76 | | 1.3 | 1.3 |
| Layer 1 | 20.7 | 1.93 | 10.7 | 0.31 | 0.66 | | 1.1 | 1.2 |
| Layer 2 | 21.9 | 1.85 | 11.8 | 0.27 | 0.84 | | 1.2 | 1.4 |
| Layer 3 | 23.1 | 1.78 | 13.0 | 0.24 | 0.91 | 0.94 | 1.3 | |
| Layer 4 | 21.7 | 1.86 | 11.6 | 0.27 | 0.82 | | 0.88(wires only) | 0.96(wires only) |
| Gnd Strap | 19.8 | 2.41 | 8.2 | 0.16 | 0.07 | 0.08 | NA | NA |
| Portcard Cable | 14.9 | 4.36 | 3.42 | 1.3 | | | | |

TABLE X. Cable properties